

# The Use of Vanadium in Flat Rolled Products

P.S. Mitchell

Chairman, Vanitec, Winterton House, High Street, Westerham, Kent TN16 1AQ, England.

## Introduction

Microalloying, using vanadium, has been a feature of the manufacture of high strength, formable, tough, flat rolled steels since the start of their more widespread production and use in the late 1950's/early 1960's. It is the purpose of this paper to give some data on the consumption of vanadium, as a whole, and to look at some of the reasons why vanadium is used in flat rolled steels.

## 1. Consumption of Vanadium

By far the majority of vanadium consumed, worldwide, is used by the steel industry.

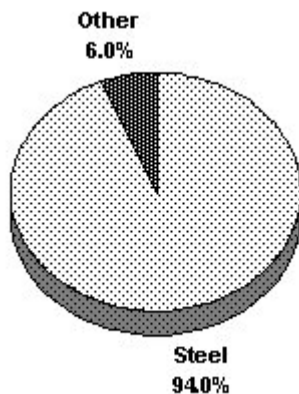


Figure 1 Consumption of vanadium in steel and other industries.

Figure 1, compiled from data in the US Geological Survey<sup>(1)</sup> indicates that, in 2004, 94% of vanadium used was consumed by the steel industry and 6% by all other uses.

Figures 2 and 3 show data on steel production and vanadium consumption over a number of past years.

Figure 2 indicates that in 2004 steel production reached a record level of 1.036

billion tonnes, driven largely by increases in steel production in China.

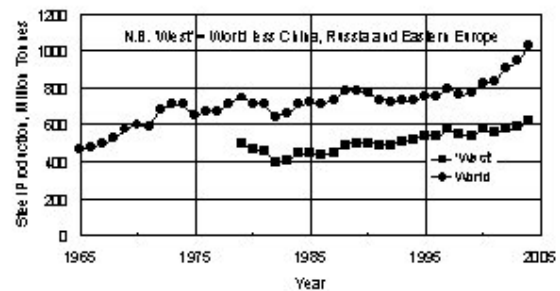


Fig. 2 Steel Production in the world and the "West".

Figure 3 illustrates that this record steel production was accompanied by record vanadium consumption, at an estimated level of 55300T of vanadium. While consumption of vanadium did increase in all major economies, the increase was particularly marked in China driven by, among other uses, the use of vanadium in high strength reinforcing bars.

It is important to note that not only did the overall consumption of vanadium increase but its consumption intensity increased also.

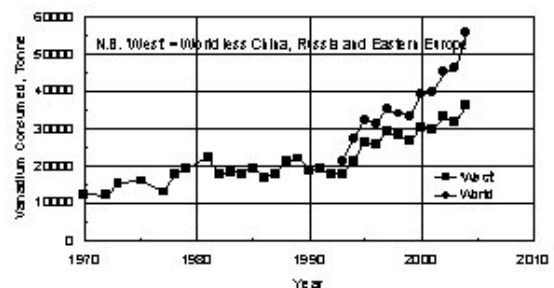


Fig. 3 Vanadium consumption in the world and the "West".

Figure 4 shows that, worldwide, in 2004 this reached a new level of 0.053kgV/tonne of steel produced.

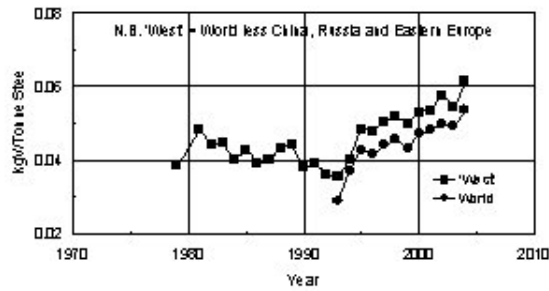


Fig. 4 Consumption of intensity of vanadium use.

It is worth noting that, in China, the consumption intensity increased by 15% from 0.034kgV/tonne of steel to 0.039kgV/tonne steel (Figure 5).

This level is still significantly below the levels of consumption intensity observed in the USA, Europe and Japan suggesting that there is still much work to be done.

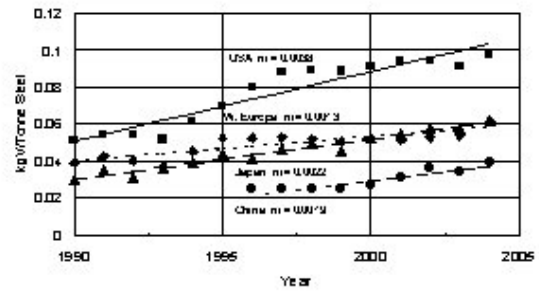


Fig. 5 Consumption intensity of vanadium in China and other countries.

## 2. Use of Vanadium in Steel

Figure 6 shows the use of vanadium in steel in Germany, Japan and the USA.

In most cases, vanadium is used in high strength, or higher value, steels, bringing benefits to both the steel manufacturer and steel user. Some of the technology of their use will now be examined.

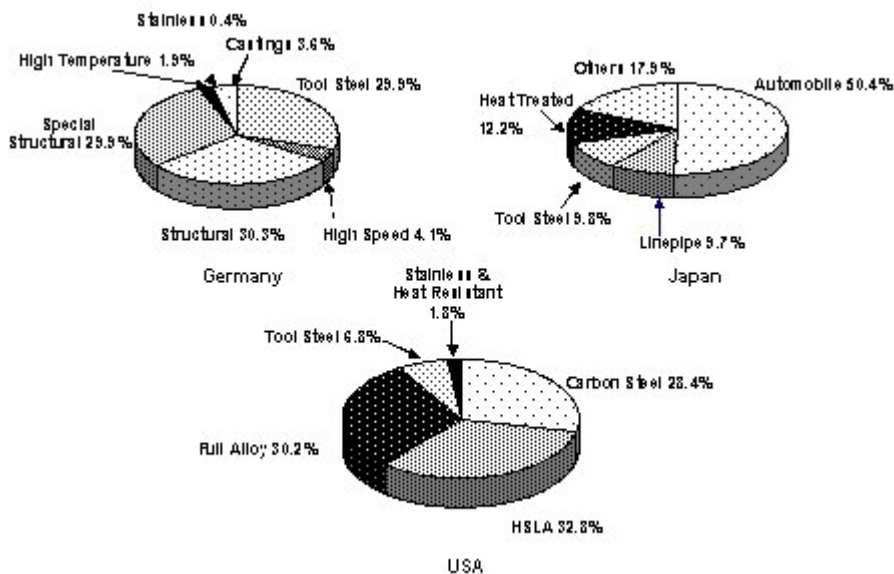


Fig. 6 Consumption of vanadium by end use in Germany, Japan and the USA.

## 2.1 Casting and Solidification

### 2.1.1 High Temperature Ductility

During casting it is important that the solidifying shell has sufficient strength and ductility to withstand the strains imposed by both the nature of the steel and the casting process. One area in which this is important is in the region of and just below the mould.

Figure 7<sup>(2)</sup> shows hot ductility curves, determined at different temperatures from the solidus down to 1100°C, for three steels. The base composition of the steels was 0.05%C–0.04%Si–0.005%S–0.004%P/0.025%/0.045%Al. The steels containing 0.8%Mn had residual levels typical of BOF steelmaking while that containing 0.4%Mn had residual levels more typical of EAF steelmaking,

including a copper content of 0.4%Cu. Both of the higher manganese steel exhibited a ductility trough in the region of 1450°C–1250°C, irrespective of whether vanadium was present or not. The steel containing 0.4%Mn along with high residuals and 0.07%V exhibited no trace of a ductility trough.

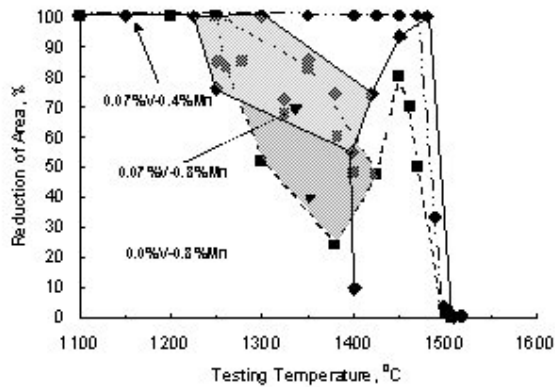


Fig. 7 High temperature ductility of the three steels from the solidus down to 1100°C.

Examination of the fracture surfaces of the steels exhibiting ductility troughs revealed that the fractures were intragranular and evidence of “dendritic” MnS particles, along with semi-continuous rows of MnS, was obtained (Figure 8).



Fig. 8 Dendritic and semi-continuous MnS particles associated with low ductility.

The low level of ductility is thought to be due, therefore, to MnS precipitation, although some effects of residuals cannot be ruled out. Vanadium appears to play no part in the development of this ductility trough.

## 2.1.2 Ductility in the Region of the Austenite - Ferrite Transformation Temperature

It is well known that transverse cracking is caused by a lack of ductility in the region of the  $\gamma \rightarrow \alpha$  transformation temperature, particularly when this coincides with the application of strain such as at the unbending point.

Figure 9 shows the results from 50mm thick, 150mm wide, hot bend tests, where three-point bending was carried out at different temperatures during cooling from casting. The measurement criterion used was the length of the longest crack propagating from the tension surface.

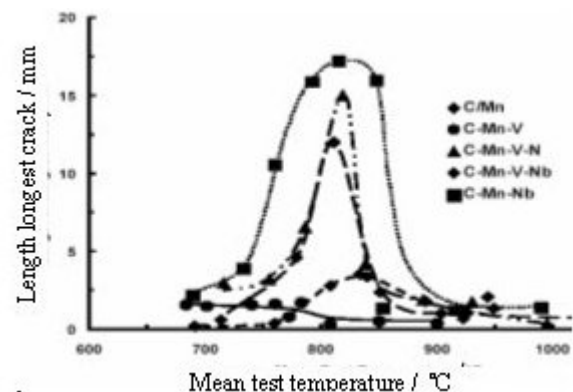


Fig. 9 Hot ductility associated with the austenite/ferrite transformation.

The results show that vanadium steels with normal nitrogen levels (0.008%N) should have a level of ductility similar to that of C-Mn steels. On the other hand, the niobium steel tested, as expected, had both the longest crack and the widest cracking envelope of all of the steels examined. The V-N and V-Nb steels were intermediate between these two extremes.

The results clearly demonstrate that vanadium-containing steels should exhibit a lower level of, if any, transverse cracking. Consequently, steel yields should be higher when using vanadium containing steels and rectification costs should be lower than those

which can be observed when manufacturing niobium containing steels.

## 2.2 Reheating or Holding for Rolling

### 2.2.1 Effect of Vanadium and Nitrogen on Equilibrium Dissolution Temperature

The solubility of both VC and VN is relatively high, that of the carbide being significantly the greater of the two<sup>(3)</sup>. Figure 10 shows the equilibrium dissolution temperature of VN, as a function of the levels of both vanadium and nitrogen.

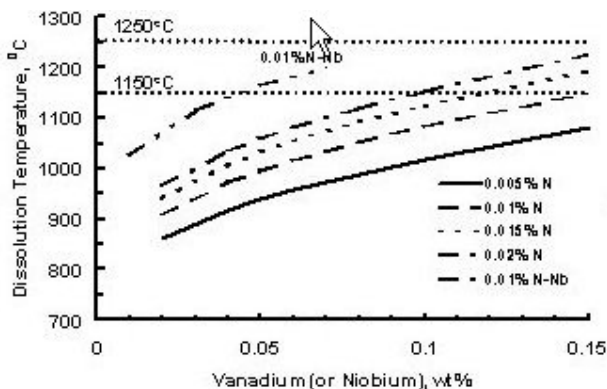


Fig. 10 Equilibrium dissolution temperatures for VN and NbCN.

In a steel containing, 0.15%V–0.02%N, i.e. quite high levels, all of the vanadium and nitrogen would be in solution at a typical reheating temperature of 1250°C, the dissolution temperature being 1226°C.

Even at 1150°C 0.1%V, in association with 0.02%N, would be in solution and the lower the vanadium or nitrogen level, the more vanadium can be taken into or retained in solution. Consequently, vanadium containing steels are capable of being reheated to or rolled from comparatively low temperatures while having significant amounts of the strengthening elements vanadium and nitrogen in solution.

For comparison, the solubility of niobium in austenite for a steel containing 0.06%C–0.01%N is also given in Figure 10. It is significantly lower than that of vanadium and at 1150°C is approximately 0.04%Nb, falling as the temperature is reduced.

This feature of the use of vanadium will become increasingly important in future as oil and other energy prices grow.

### 2.2.2 Potential Effects of Titanium and Aluminium

In the V-N microalloying system, the efficiency of vanadium utilisation improves as the nitrogen level approaches and possibly slightly exceeds the stoichiometric ratio with vanadium. Also, if titanium is added, the stability of TiN is significantly greater than that of VN. As a result, when titanium is added to a vanadium-containing steel there is a tendency to form relatively coarse, complex (Ti-V-N), precipitates at high temperature. Being coarse, these precipitates do not participate in strengthening and they reduce the amount of nitrogen available for reaction with vanadium during or after the  $\gamma \rightarrow \alpha$  transformation, thus lowering the efficiency of the system.

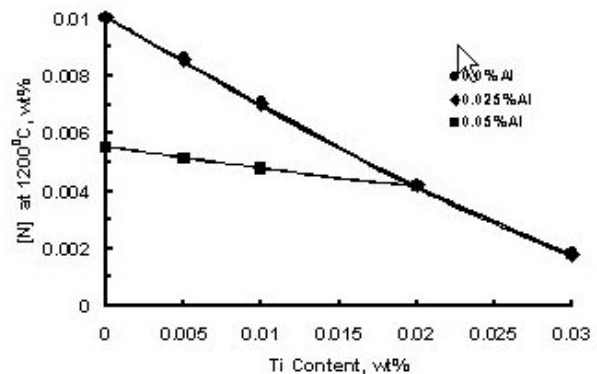


Fig. 11 Effect of Ti and Al on the nitrogen in solution at 1200°C for a 0.05%V–0.01%N steel.

Figure 11 depicts that, for a 0.06%C–1.35%Mn–0.05%V–0.01%N steel, the level of nitrogen in solution at 1200°C, at equilibrium, falls quite dramatically with increasing titanium level. The figure also shows that below 0.02%Ti the extent of the fall in nitrogen level in solution is quite dependent on the aluminium content, especially at higher levels of aluminium. This effect of aluminium becomes even more marked with reduction in temperature. Thus, when manufacturing vanadium containing steels it is necessary to keep both the titanium and aluminium levels as low as possible and when reheating, in the case



of aluminium, to ensure that the reheating temperature is above the dissolution temperature of AlN in the steel.

### 2.2.3 Effect of Reheating Temperature on Austenite Grain Size

One of the consequences of relatively low dissolution temperatures is that grain coarsening temperatures during reheating for rolling also tend to be low, there being too few precipitates with too large an interparticle spacing to effectively pin the austenite grains.

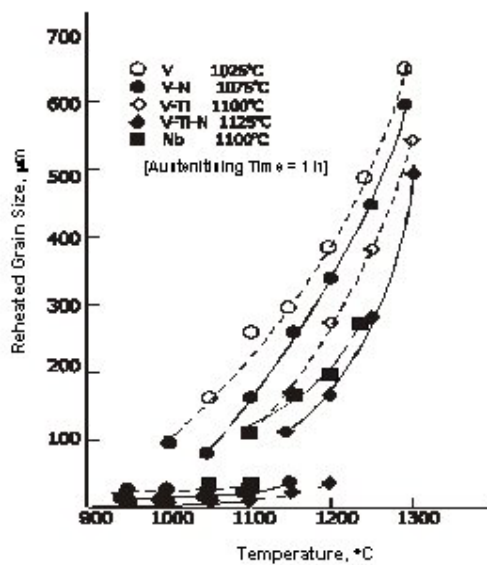


Fig. 12 Austenite grain-coarsening temperatures for a number steels.

Figure 12<sup>(4)</sup> suggests that for a lower nitrogen, vanadium microalloyed, steel the grain coarsening temperature is of the order of 1025°C and that this temperature can be increased by increasing the nitrogen level and by adding titanium, although the remarks about the use of titanium contained in Section 2.2.2 have to be borne in mind.

Also, as will be noted later, a coarse austenite grain size at this stage of processing is relatively unimportant in vanadium microalloyed steels, as it is still possible to obtain a fine ferrite grain size after rolling. This is particularly important in thin slab cast steels, where the austenite grain size can be as large as 1mm, or more.

## 2.3 Rolling and Finishing

### 2.3.1 Solute Drag, Precipitation and Recrystallisation

The main factors affecting recrystallisation of C-Mn steels during rolling are strain, strain rate, temperature and initial austenite grain size. In micro-alloyed steels, solute drag and precipitation also need to be taken into consideration.

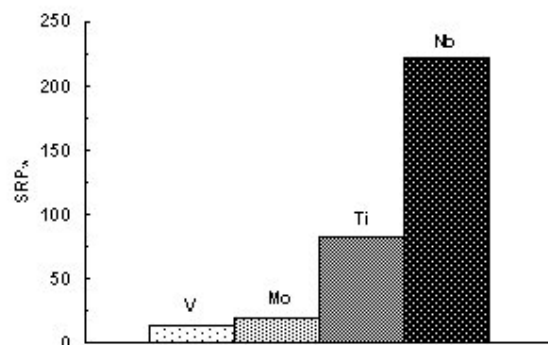


Fig. 13 Solute retardation parameters for V, Mo, Ti and Nb.

Figure 13<sup>(5)</sup> illustrates the effect of a 0.1% addition of Mo, Nb, V or Ti, in solution in austenite, on the solute retardation parameter, compared with that of a C-Mn steel. From this it is clear that the solute drag effects during rolling of molybdenum and vanadium are small, compared with those of titanium and particularly niobium.

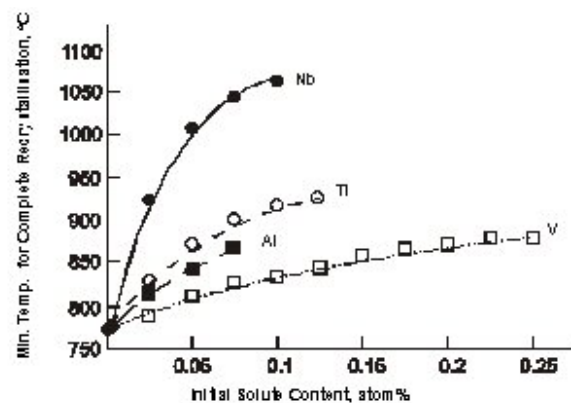


Fig. 14 Effect of Microalloying on the recrystallisation of austenite.

Furthermore, as a result of their relatively high solubility in austenite, precipitation of VN and VC is normally inhibited until relatively low rolling temperatures are reached and, even

then, tends to occur only at higher levels of vanadium and nitrogen.

The overall effect is that in vanadium containing steels the recrystallisation stop temperature is relatively low, Figure 14.

Consequently, in such steels, austenite grain refinement can proceed by the normal processes of deformation, recovery and recrystallisation, over a wide range of temperature, unlike niobium containing steels where recrystallisation stops at relatively high temperatures

### 2.3.2 Grain Size

Figure 15 shows an example of the level of austenite grain refinement obtained when rolling a 0.1%V–0.02%N–0.008%Ti steel, which had an initial austenite grain size of 1mm (as cast). After 76% reduction in four passes, from 50mm thick to 12mm thick, in the temperature range 1150°C–950°C, the austenite grains appear to have recrystallised and the grain size was of the order of 22 $\mu$ m.

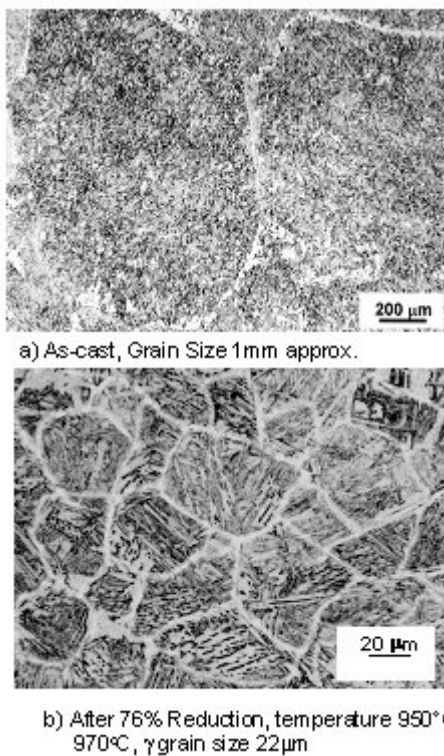


Fig. 15 Austenite grain refinement obtained on rolling a 0.1%V-0.02%N-0.008%Ti steel.

It would also appear that the recrystallised austenite grain size remains reasonably constant over a fairly wide range of temperature, as shown in Figure 16<sup>(4)</sup>. In this figure there are marked effects of both nitrogen and titanium on the austenite grain size but, for any one compositional type, the effect of rolling temperature on grain size is small.

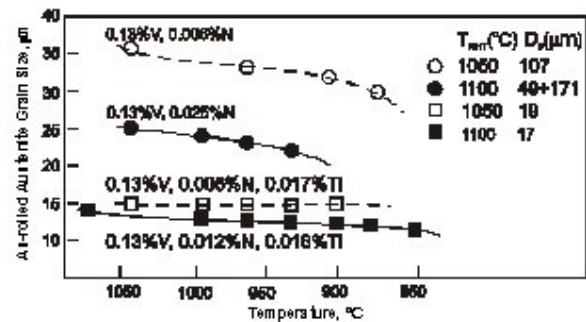


Fig. 16 Effect of rolling temperature on the austenite grain size in a number of steels (50% reduction,  $\dot{\epsilon}=4.9$ -6.9s<sup>-1</sup>)

Furthermore, by applying the principle of recrystallisation controlled rolling to vanadium containing steels, it is possible to achieve austenite grains with a sufficiently high grain boundary surface area/volume ratio to ensure transformation to fine ferrite. Figure 17<sup>(7)</sup> illustrates the possibility of achieving a fine ferrite grain size by adopting this technique.

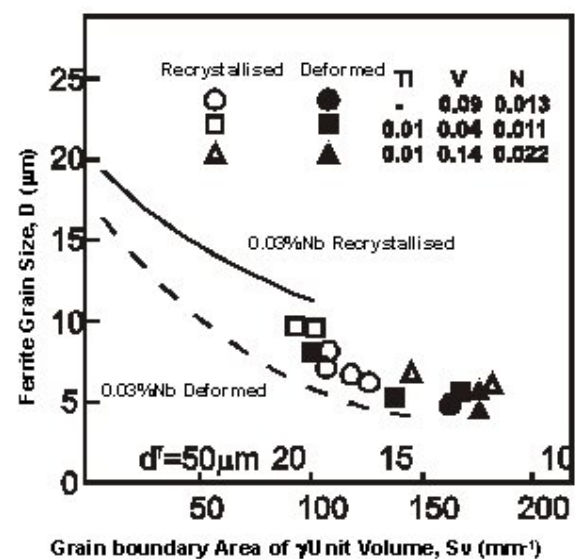


Fig. 17 Effect of austenite grain boundary surface area/volume ratio on ferrite grain size.

Alternatively, in flat rolled steels, where the transformation temperature can be adjusted by control of the cooling and coiling conditions, it is also possible to achieve fine ferrite grain size without the need to resort to heavy controlled rolling.

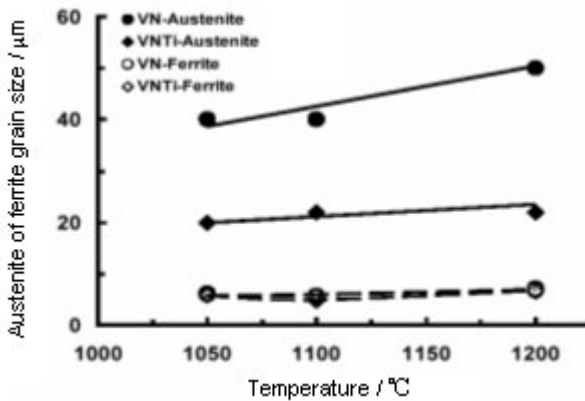


Fig. 18 Effect of equalisation temperature on the austenite and ferrite grain size.

Figure 18 shows the effect of equalisation temperature, during thin slab casting, on both the austenite and ferrite grain sizes of V-N and V-N-Ti steels. After 76% reduction from 50mm to 12mm in the temperature range 1150°C – 950°C the austenite grain size of the V-N steel had been reduced from 1mm (as cast) to 40 - 50μm while that of the V-N-Ti steel had been reduced from 1mm to 20-22μm. However, with one further pass, giving total deformation of 86-88%, followed by controlled cooling at 17°C/sec to a coiling temperature of 600°C, the ferrite grain size obtained was 5-7μm, irrespective of whether titanium was present or not and more or less independent of the equalisation temperature. This level of grain size is just as fine as that obtained by controlled rolling.

### 2.3.3 Rolling loads and Productivity

As a direct result of the recrystallisation behaviour of vanadium containing steels rolling loads tend to remain relatively low. Figure 19<sup>(6)</sup> shows a comparison of measured rolling loads, converted to flow stresses using Sims equation, the loads having been measured on the finishing stands of a hot mill. The flow stress of the vanadium-containing steel did increase with reduction in temperature but the

rate of increase was similar to that of the C-Mn steel. No increase in flow stress arising from solute drag or precipitation was observed in the vanadium steel. On the other hand, in the niobium-containing steel, a significant increase in flow stress was observed at temperatures below about 950°C. The effect of this was that at 850°C the average flow stress of the niobium steel was some 84% higher than that of the vanadium steel.

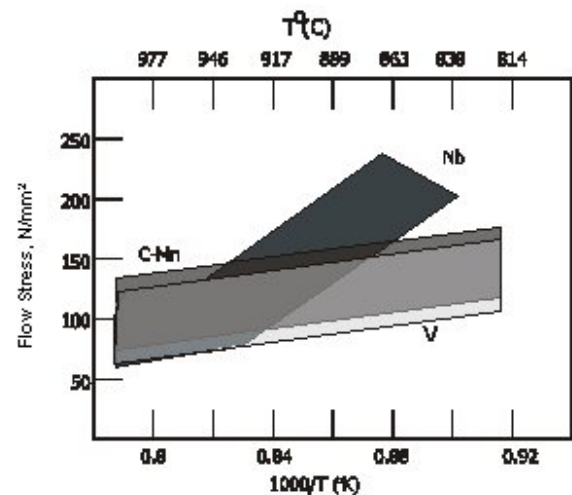


Fig. 19 Comparison of the flow stress during rolling for C-Mn, V and Nb steels.

A result of the above features is that, when rolling vanadium microalloyed steels, it should be possible to roll from more energy efficient, lower, temperatures with faster furnace pushing rates and higher rolling rates than would be typical of niobium microalloyed steels.

Table 1 Slab reheating and rolling parameters.

	Coiling Temp., °C	Time in furnace zone, min					Computed temp. in furnace	
		Z1	Z2	Z3	Z4	Total	Core, °C	Average, °C
V-Heat	CT600							
	CT 620	55	20	30	25	130	1168	1177
	CT 600						1177	1186
	CT 610	30	23	27	26	106		
	CT 620						1168	1178
S355+Nb		40	40	30	20	130	1190	1200

Table 1 shows a comparison of rolling 0.01%Nb and 0.03–0.04%V steels, which were otherwise identical. In V-Heat 2 the soaking temperature of the vanadium-containing steel was reduced to 1177°C – 1186°C, compared with 1200°C for the niobium steel.

Additionally, the furnace heating time for the vanadium steel was found to be 18.5% lower at (106 minutes) than that of the niobium steel (130 minutes). In the particular rolling mill involved, where all heated slabs can be rolled, this constitutes a significant increase in mill productivity and it is believed that the heating time of the vanadium containing steel could be reduced further, leading to additional improvement in productivity.

### 2.3.4 Effects of End Water Cool Temperature and Coiling Temperature on Properties

After rolling, two of the more important parameters controlling mechanical properties are the temperature at which water cooling after rolling is stopped and the coiling temperature. These parameters would be expected to affect the ferrite grain size and the levels of precipitation strengthening, both of which have a significant effect on mechanical properties.

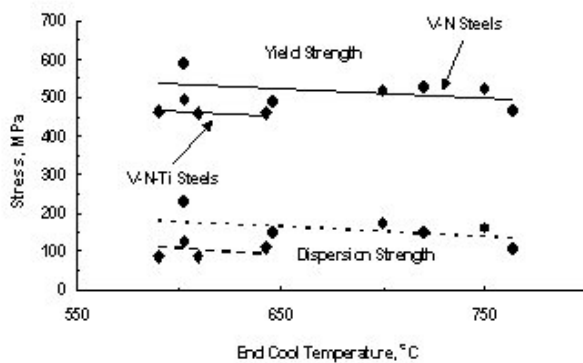


Fig. 20 Effect of end water cool temperature on yield strength and dispersion strengthening in V-N and V-N-Ti strengthened steels.

Figure 20 gives an indication of the effect of end water cool temperature on the levels of yield strength and dispersion strengthening in 0.1%V–0.02%N and 0.1%V–0.02%N–0.008%Ti steels, which had been finish rolled at 850°C–900°C, cooled at 17°C/sec and coiled at 600°C. As the end water cool temperature decreased from 760°C to 600°C the yield strength increased by about 40MPa, on average. This increase in strength was almost, if not all, due to dispersion strengthening, as

can be seen from the lower line in Figure 20. The effect of titanium was quite marked, both the level of yield strength and of dispersion strengthening being reduced by 60-70MPa below that of the V-N steel. This decrease was due to the formation of the coarse, complex, Ti-V-N, precipitates noted earlier, these precipitates being too large to participate in strengthening.

The effects of coiling temperature and nitrogen level on the yield strength of a 0.13%C–1.4%Mn–0.5%Si–0.12%V steels are shown in Figure 21<sup>(8)</sup>.

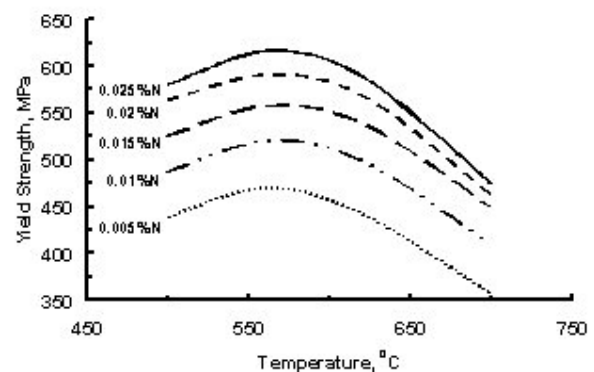


Fig. 21 Effect of coiling temperature and nitrogen level on the yield strength of 0.12%V steels.

This demonstrates that, over the full range of nitrogen level, peak yield strength was achieved in the coiling temperature range 550–600°C. From the above comments on end water temperature it is clear that to optimise yield strength this parameter should be as close to this coiling temperature as possible.

### 2.4 Effects of Vanadium and Nitrogen on Properties

As has already been noted, the strength of vanadium containing steels is related to the nitrogen content, especially at lower levels of carbon. Figure 22 shows the effect of both vanadium and nitrogen on the yield strength and the level of dispersion strengthening in 0.06%C/1.35% - 1.55%Mn / 0.15% - 0.4%Si / 0.015% - 0.04%Al steels.

The steels had been rolled from 1100°C – 1150°C, to 6-7mm thick strip and coiled at 600°C. In this figure, different levels of



vanadium and nitrogen have been combined into a VxN product.

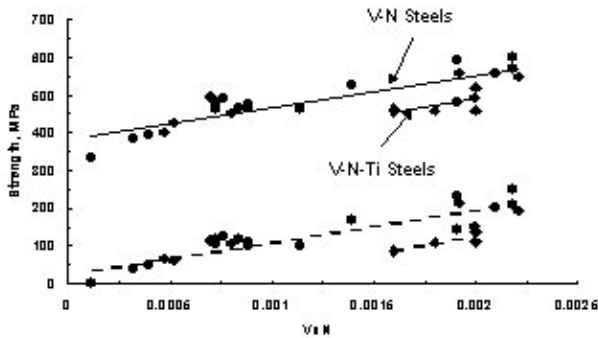


Fig. 22 Effect of V and N on yield strength and dispersion strengthening.

As the VxN product increased from 0.0 to 0.002 (0.1%V–0.02%N) the yield strength increased from a level just above 350MPa to a level above 550MPa. Most of this increase was due to dispersion strengthening. The significant deleterious effect on yield strength of a small (0.008%Ti) addition can also be seen.

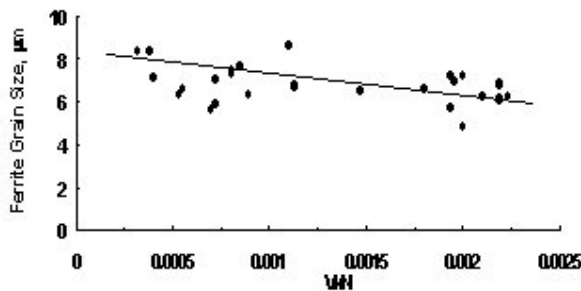


Fig. 23 Effect of V and N on the ferrite grain size.

Figure 23 shows the effect of the VxN product on the ferrite grain size of the steels examined and demonstrates that as the VxN product increased the grain size became more refined.

The contributions to yield strength from grain size and dispersion strengthening for the steels in Figure 22 are shown in Figure 24. As the VxN product increased the contribution to yield strength from grain size decreased from approximately 60% to just less than 40%, while that from dispersion strengthening increased from 0.0% to just less than 40%. In the titanium treated steels, the contribution from grain size was 45%, while that from dispersion strengthening was 28%.

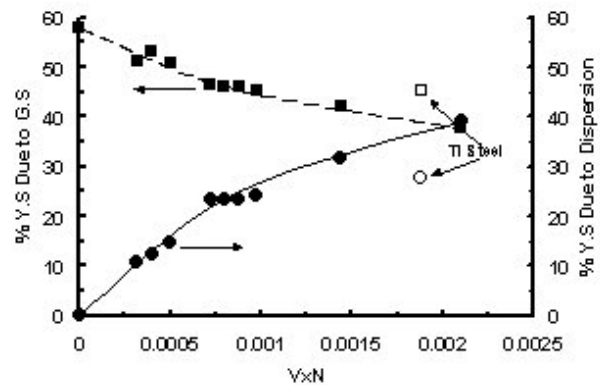


Fig. 24 Contributions of ferrite grain size and dispersion strengthening to yield strength.

From Figures, 22 – 24 it is clear that, by control and adjustment of the addition of vanadium and nitrogen, it is possible to obtain a wide range of yield strength levels in steels micro-alloyed with vanadium alone.

Such steels can also have good levels of toughness as is apparent in Figure 25.

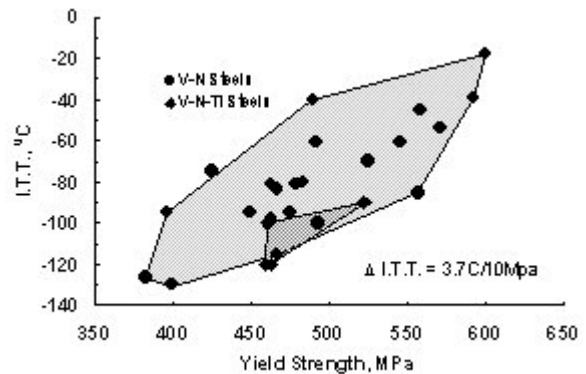


Fig. 25 Effect of yield strength on ITT in V-N and V-N-Ti microalloyed steels.

The range of I.T.T. observed varied from  $-130^{\circ}\text{C}$  to  $-20^{\circ}\text{C}$ , depending on the yield strength of the steel. The rate of increase of I.T.T. with increasing yield strength ( $3.7^{\circ}\text{C}/10\text{MPa}$ ) is typical of what would be expected from dispersion strengthened steels. While the Ti-treated steels were towards the lower end of the scatter band, they were, in fact, still within it. It would appear, therefore, that there is little significant overall benefit to be gained from adding titanium to vanadium microalloyed strip steel.

## 2.5 Weldability

It is likely that vanadium containing flat product steels will be welded using a wide range of welding processes. Among these processes will almost certainly be laser welding and spot welding.

### 2.5.1 CO<sub>2</sub> Laser Welding

Welding lobe diagrams for low carbon, 0.05%V steels containing 0.005%N and 0.01%N are shown in Figure 26.

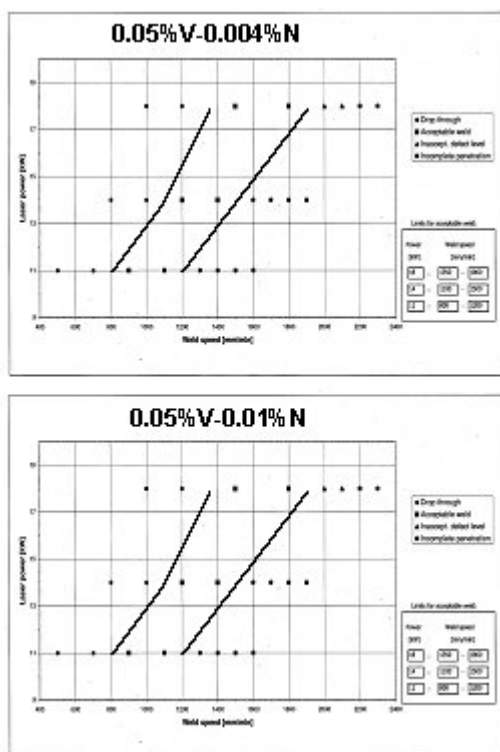


Fig. 26 Welding lobe diagrams for laser welded 0.05%V steel.

It should be noted that increasing the vanadium level to 0.1% made little difference to these diagrams. They show that vanadium-containing steels can be successfully welded by laser over a reasonably wide range of laser power and welding speed.

Figure 27 depicts a typical heat affected zone microstructure for a laser weld in a steel containing 0.1%V. This contained over 30% tough, intragranular ferrite and is reflected in the weld impact transition temperature of  $-100^{\circ}\text{C}$ , which is shown in Figure 28.

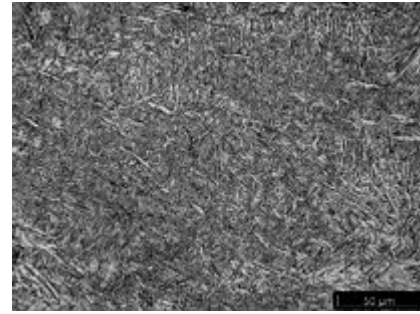


Fig. 27 Weld microstructure for a laser welded 0.1%V steel.

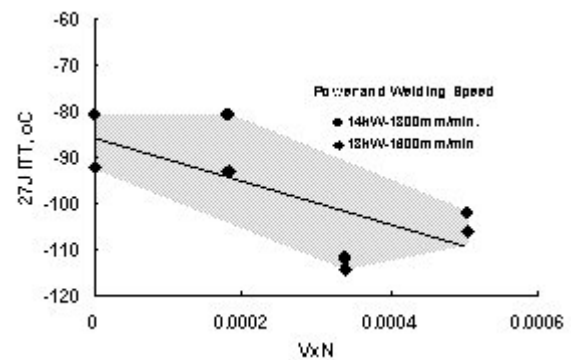


Fig. 28 Effect of V and N on the ITT of laser welded, microalloyed steel.

### 2.5.2 Spot Welding

Spot-weld growth curves for 5.2mm and 2.4mm thick strip, containing 0.05%V–0.011%N, are shown in Figure 29. These show that vanadium-containing steels can also be spot welded over a satisfactorily wide range of weld current and diameter.

The maximum hardness of the welds was typical for the carbon equivalent value of the steel and is shown in Figure 30.

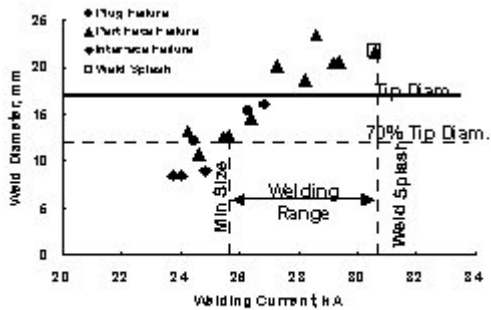
Figure 31 shows results of static shear and cross tension tests for vanadium containing steels and compares the results with those of a steel containing 0.03%Nb.

Once again the results are typical of those of microalloyed steels of similar strength level.

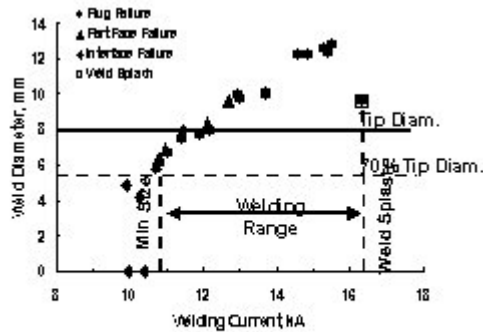
Finally, a comparison of fatigue test data, shown in figure 32, indicates that the fatigue performance of the vanadium containing steels was at least as good as those of other C-Mn and HSLA steels.

These results on laser and spot welding, taken along with other results on the conventional metal-arc, fusion welding of

vanadium containing steels<sup>(9-10)</sup>, would suggest that there should be little difficulty welding vanadium containing steels over a wide range of welding processes and welding conditions.



a) 5.2mm Thick, 17mm Electrode Tip Diameter, 32kN Electrode Force



b) 2.4mm Thick, 8mm Electrode Tip Diameter, 7kN Electrode Force

Fig. 29 Spot weld growth curves for 0.05%V-0.011%N steel.

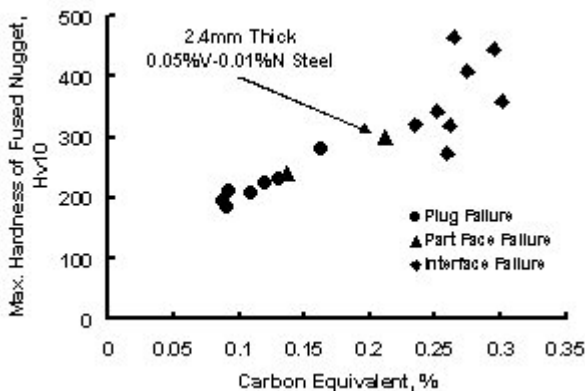


Fig. 30 Effect of CEV on the maximum hardness of spot welds on 0.05%-0.011%N steel.

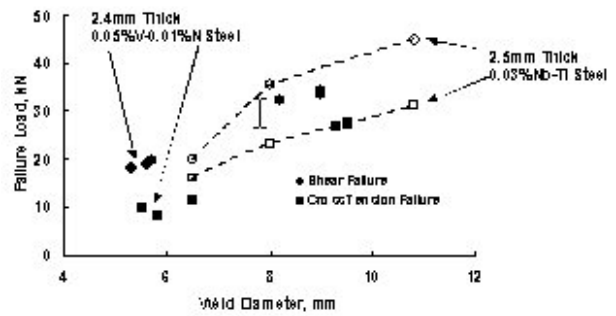


Fig. 31 Comparison of shear and cross tension tests for spot welds in V-containing and Nb-Ti steels.

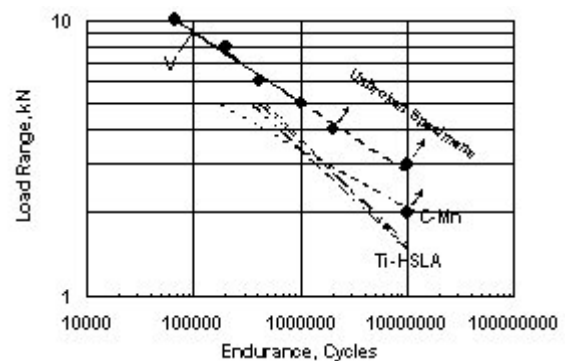


Fig. 32 Fatigue data for V-containing and other C-Mn and HSLA steels.

### 3. Conclusions

3.1 Worldwide consumption of vanadium and its consumption intensity both reached record levels of 55,300 and 0.053kgV/t steel, respectively, in 2004.

3.2 In most cases, vanadium is used in higher strength or higher value steels.

3.3 The reasons for using vanadium include:-

- Relative freedom from cracking during continuous casting of vanadium containing steels.
- Ability to soak vanadium containing steels for rolling at relatively low temperatures.
- Vanadium does not inhibit recrystallisation of austenite during rolling until low temperatures are reached, usually in combination with high V and N levels.
- Consequently, vanadium micro-alloyed steels exhibit low rolling loads with the potential to greatly increase productivity.



- Because vanadium-containing steels recrystallise during rolling, they can develop fine austenite and ferrite grain sizes.

- Fine ferrite grain size can also be produced by control of the cooling and coiling conditions after rolling.

- By adjustment and control of the V and N additions it is possible to produce steels with a range of strength level and which have good toughness, the level of which depends on strength.

- Vanadium micro-alloyed steels should be capable of being welded by a wide range of welding processes, including laser and spot welding.

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